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RONALD REAGAN, Governor

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DIVISION OF HIGHWAYS

AND RESEARCH DEPARTMENT

FOLSOM BLVD., SACRAMENTO 95819

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Final Report
M&R No. 642114

Mr. R. J. Datel
State Highway Engineer

Dear Sir:

Submitted herewith is a research report titled:

SETTLEMENT STUDY AT BRIDGE APPROACHES

By

BEN ZEILER AND W. F. KLEIMAN

Supervised by .... A. D. Hirsch
Directed by .... Travis Smith

Very truly yours,

JOHN L. BEATON
Materials and Research Engineer

REFERENCE: Zeiler, Ben; Kleiman, William F.; Smith, Travis; Hirsch, Albin D., "Settlement Study at Bridge Approaches," State of California, Department of Public Works, Division of Highways, Materials and Research Department. Research Report CA-Hwy-MR 642114(2)-72-19, April, 1972.

ABSTRACT: Excessive differential settlement of the road surface at bridge abutments creates a driving hazard and often requires periodic maintenance work. Over 900 field settlement records of approach embankments to structures located throughout California were collected for analysis. A major portion of the correlational work was accomplished by optical coincidence methods. Settlement vs. log-time plots were prepared and pertinent soil test data affixed to each plot. Only recorded settlements of the foundation soil of 0.20 ft. or greater were included in this study. Variables relating time-settlement characteristics to different soil types were analyzed. Soil information was limited to sample borings and penetrometer data. Actual and contract waiting periods were analyzed in conjunction with surcharge data. Benefits of surcharge vs. nonsurcharge data are described.

The failure to find detectable correlation between soil data and other parameters forced the researchers to abandon further work on this project.

KEY WORDS: Settlements, differential settlement, bridge abutments, approach embankments, settlement rate, field measurements, correlations, data processing.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to the construction and materials personnel of the various Districts of the California Division of Highways for their assistance in installing and reading settlement units during the past twenty years.

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INTRODUCTION

Excessive differential settlement at bridge abutments introduces safety hazards and results in costly maintenance. Small differential settlement can result in driver discomfort. As the distorted profile increases in magnitude the likelihood of serious accidents increases. When differential settlement at the paving notch exceeds some minimal amount the jolt may be of such intensity that the motorist may momentarily lose control of his car. A sag of several feet in the profile grade can be tolerated if the sag is distributed along an embankment of great length, say, 800 ft to 1000 ft, but a hazardous situation develops if differential settlement on the order of 0.2 ft occurs immediately at the paving notch of a structure. As a corrective measure to this hazardous situation, routine patching becomes necessary to restore the road surface to profile grade.

In addition to the substantial annual maintenance cost required to treat this problem, additional complications arise. In order to perform the necessary maintenance work the orderly flow of traffic must be interrupted, thereby creating another type of safety hazard as well as delay to the travelling public. Maintenance operations in heavy traffic are nearly impossible at some locations in California without bringing traffic to a standstill.

The elimination of all differential settlement may be impossible of achievement since a structure is usually founded on spread footings resting on firm material or piles driven to firm material and hence will undergo minor settlement, if any. In contrast, the approach embankment is constructed of soil and rock founded on soil and rock which is, to a greater or lesser degree, always compressible. While differential settlement at the pavement notch can be attributed to settlement of the foundation soil, compression within the embankment, or some other factors, this study is limited only to an analysis of the former.

Early in 1952 the Materials and Research Department initiated a program to investigate differential settlement which occurs between bridges and their approach embankments. Settlement records were obtained from projects where settlement platforms had been installed for purposes of construction control. These settlement units were installed at original ground to determine when pile driving operations could commence and were not installed as part of any research project. Consequently, undisturbed sampling (and subsequent consolidation testing) was not warranted since the shape of the settlement vs time plot provided the engineer with sufficient information to decide when pile driving could begin.

The purpose of this research project is to classify and correlate the enormous bulk of settlement data which has been accumulated during the past 20 years, with the intent that underlying relationships between soil types, settlement characteristics, and control measures would be uncovered. The benefits derived from such an undertaking would thereby enhance the predictive quality of identifying anticipated problem areas on future highway projects. Such advance warning would serve to focus attention on possible reconsideration of construction priorities, e.g., surcharge and extensive waiting periods, reduced embankment height or possibly other special treatment (other research is currently being conducted on specific construction procedures for controlling the bump problem, M&R Research Number 632400, FHWA No. D-4-35).

CONCLUSIONS

A comprehensive study to determine in a statistically precise way the factors contributing to settlement at bridge approaches has resulted in a limited amount of new knowledge. A general benefit of this research report has been to carefully detail the procedures used by the researchers which may in turn be of some value on future studies on this subject.

The conclusions listed below fall into three categories: (A) new knowledge not previously established; (B) confirmation of previous known theory and practice; and (C) major questions left unanswered in this research project.

(A) New Knowledge Not Previously Established

Various correlational studies were performed between field settlement records and Maintenance Department reports of adverse step-offs at the pavement notch. Results indicate that in those cases where surcharges were employed there were no significant differences in the various soil indices calculated irrespective of whether surcharges were left in place longer than 50% in excess of or 50% or less than the stipulated contract waiting period. There is sufficient evidence to suggest that a differential bump of 0.20 ft at the bridge approach at 1,000 days after the embankment is constructed may not be a low enough criterion. A significant number of distress cases were reported by the Maintenance Department where a differential of 0.10 foot or less exists between the time the surcharge was removed and settlement at 1,000 days.

The use of optical coincidence as a method of researching data was found to be highly efficient and is recommended for use when large numbers of multiple variables must be analyzed.

(B) Confirmation of Previously Known Theory and Practice

Surcharges are effective in increasing the rate of settlement of foundation soils and are found to be generally beneficial over relatively short periods of time (30 days).

The effect of surcharge is to significantly reduce the percent residual settlement which is associated with the long-term bump problem. At the highest values of percent residual settlement, nonsurcharge data occurs with an incidence of approximately 2½ times that of surcharge data.

(C) Major Questions Left Unanswered in this Research Project

No significantly positive correlation was found between cumulative field settlement measured up to 1,000 days after an embankment is constructed and the degree of compressibility assigned to the underlying soil layers. The unfruitful results of the various soil correlational studies force us to conclude that this overall problem is unsolvable with the limited soils information available in this study.

No specific recommendations are offered as a general solution to the bump problem based upon the current study. Instead, each proposed approach embankment appears to warrant individual analysis.

RECOMMENDATIONS

1) A foundation investigation is recommended for each approach embankment and the extent of the investigation should be based upon the types of foundation material encountered.

2) The soil mechanics approach is accepted by most soils engineers as a more reliable method of determining magnitude and rate of settlement in fine grained and clayey soils than are procedures based upon geologic classification and boring test data. The application of geologic principles appears more promising in the domain of granular or rocky material. These inferences have been substantiated in various related studies conducted on California bridge approaches. See Reference 2. Unfortunately, the kind of information available in the present study could not be used in any way to test or substantiate these generalizations.

   When a settlement problem is indicated from preliminary investigation of a particular job site, we recommend that comprehensive soil testing be conducted to predict magnitudes and rates of settlement. Any radical modification of present settlement predictive procedures should be the objective of further research in this area.

3) For some locations the intensity of the bump problem may be best alleviated by maintenance rather than by design specifications. Economic considerations would influence this design decision.

NOTATION

The nomenclature given below is used throughout this report. This information is summarized in graphical form on Figure 1.

E = Embankment Height: The maximum permanent embankment which acts on the settlement unit. Surcharge thickness is excluded from the definition of this index.

S = Surcharge Thickness: Material temporarily placed on top of the embankment to accelerate the rate of consolidation of the foundation soil.

S_{30} = Settlement at 30 days: The settlement which has occurred 30 days after the embankment has been constructed to final grade. If a surcharge is used, S_{30} is measured from the time of completion of surcharge construction. This index is found to best reflect the transition in the soils initial adjustment to the imposed load to the long-term settlement characteristics.

S_{1000} = Settlement at 1,000 days: The settlement which occurs during the first 1,000 days after construction begins. The magnitude of this variable is arbitrarily defined as representing the completion of settlement due to embankment construction. In cases where insufficient readings were obtained due either to a leveling off in the settlement curve or malfunctioning of the unit the best 1,000-day settlement is extrapolated from the data.

W_c = Contract Waiting Period: The waiting period at a particular structure as specified in the contract special provisions. The time period is that between the completion of embankment construction (including any surcharge) and the permissible driving of foundation piles as specified in the special provisions.

W_a = Actual Waiting Period: The actual time between completion of embankment construction (including any surcharge) and the onset of pile driving operations. In almost all cases our records of W_a are incomplete if no surcharge was involved.

S_{EW} = Settlement at end of Waiting Period: S_{EW} is the settlement the foundation soil has undergone up until the beginning of surcharge removal.

RS = Residual Settlement: The difference between the 1,000-day and 30-day settlements expressed in feet.

$$RS = S_{1000} - S_{30}$$

A = Residual Settlement Ratio: The ratio between the difference in the 1,000-day and 30-day settlements divided by the 1,000-day settlement.

$$A = \frac{S_{1000} - S_{30}}{S_{1000}}$$

B = Settlement/Embankment Ratio: The 1,000-day settlement divided by the embankment height. Surcharge is excluded from this index in order to later correlate surcharge heights with B factors.

$$B = \frac{S_{1000}}{E}$$

C = Residual Settlement/Embankment: The ratio between residual settlement and embankment height. This term accounts for both total magnitude of settlement in terms of embankment height (settlement/embankment ratio) and the degree of settlement problem which occurs over an extended time period.

$$C = \frac{S_{1000} - S_{30}}{E}$$

METHOD OF DATA ANALYSIS

1. SETTLEMENT VS. LOG-TIME PLOTS

Settlement data have been obtained from the Materials and Research Department files, District Materials field installation units and the Maintenance Department. Log of Test Borings, which quantitatively and qualitatively describe the native soil near or upon which the settlement unit is placed, have been obtained from the Geology Section of the Bridge Department. Figures 2 and 3 illustrate typical settlement log-time plots with corresponding soil profiles and penetrometer data.

2. OPTICAL COINCIDENCE

An optical coincidence method was utilized to simplify the analysis of the enormous amount of data. The basic equipment of this system is shown on Figure 4. The encoder-viewer consists of a light box and frame on which is mounted an electric drill attached to a sliding carriage which provides movement along both vertical and horizontal axes. There is a 0-99 scale on each axis, with stops at each unit of the scale allowing the drill to be set precisely at any one of 10,000 grid positions. Drilling is accomplished by lowering the drill and pressing a foot switch. A hole is thus punched in one or more cards in a position representing the accession number of a specific range value within each variable for each settlement log-time plot. Blocks of 500 to 3,000 squares were assigned to each of the 11 districts in the California Division of Highways. The number of assigned squares (in 500 increments) is roughly proportional to the data available from each district. By block assignment of districts, the relative geographical locations is immediately apparent during the active research phase of the project.

Based on a preliminary review of the data, each variable has been divided into ranges so that the number of holes to be punched on each card will be approximately equal. Four to six keydex cards of the same color code as assigned to each variable being studied. The variables and ranges investigated are shown on Table 1.

ANALYSIS OF DATA

1. GENERAL DISCUSSION

The data used in this study were based on the settlement records from 911 settlement units. A breakdown by District, number of structures and number of contracts is shown on Table 2.

The initial correlation studies were limited to 417 plots. Eliminated were: (1) those plots which did not have settlement readings after surcharge was removed; (2) duplicate plots which showed very similar settlement curves and soil data at one or both ends of a structure; (3) plots with insufficient data which resulted in a highly questionable estimation of S_{1000}. Unless otherwise noted all discussions will be limited to analyses performed on the above mentioned 417 plots.

2. CORRELATION OF INDEX VALUES. (EXCLUSIVE OF SOIL DATA)

For purposes of comparison, surcharge thicknesses were divided into three groups: thin surcharges, 1-3 feet; medium surcharges, 4-7 feet; and thick surcharges, 8 feet and greater. The range of surcharge thickness which distinguishes each group was based upon the general broad groupings as revealed in the distribution of data. The following general conclusions are based on a mathematical analysis of the data.

a. Residual Settlement Ratio ("A" factors) tend to be significantly less when surcharges are used.

b. The larger the surcharge the more effective is the reduction in Residual Settlement Ratio.

c. Greater surcharges are associated with greater 1,000-day settlements.

d. There is a significant percentage of cases where no surcharge conditions are associated with large Residual Settlement Factors (greater than 30%) or large settlements (greater than 1.5 feet).

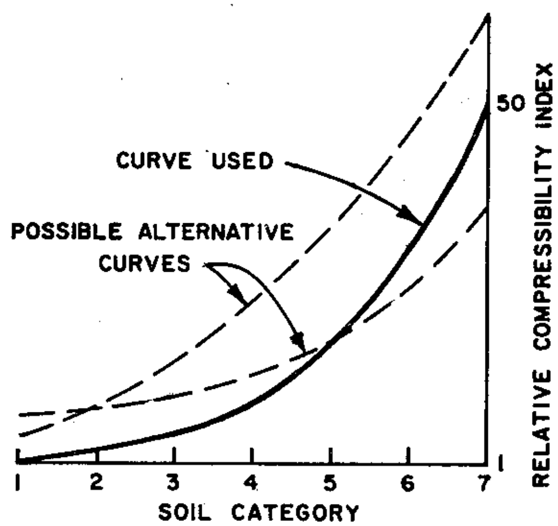
e. Residual Settlement Factors for thick surcharges are less than those associated with the combination of medium and thin surcharges.

3. CORRELATION OF SOILS AND SETTLEMENT DATA

One of the objectives of this project is to relate penetrometer values, visual and test data obtained from borings, data on embankment and settlement characteristics, and the presently defined indices. To accomplish this objective would mean to better predict amounts and rates of settlement at a particular soil site.

The following procedure was used to attempt to relate the various soil types to thousand-day settlements (S_{1000}). Based on sample borings located within 100 ft of settlement units, the boring data were grouped into seven categories ranging from highly compressible to negligibly compressible material. These groups reflect the relative settlement which can be expected per unit thickness of soil (for a given overburden pressure) after embankment construction is completed. A typical categorical breakdown is shown on Table 3. While soils engineers may debate as to which of two adjacent categories a particular soil should be placed, this kind of discrepancy has negligible effect in the way in which the data is analyzed (as will presently be described). That a particular soil type should transcend two or more categories is considered extremely unlikely and again would not unduly distort the correlational study to be described.

After placement of soils into the various categories a relative compressibility factor was assigned to each category. These factors represent the relative compressibility of a soil of any category with respect to soil Category 1 (least compressible). An idealized exponential curve was used to facilitate this procedure. The curve used is shown below:



For example, a soil of Category 7 (e.g., soft clay) is found to be 50 times as compressible as a soil of Category 1 (e.g., loose silty gravelly sand). Whether the arbitrary dependent variable values selected as depicted by "actual curve used" are better than one of several possible alternative curves is of little consequence in analyzing the data, provided that the curve used conforms to an exponential function. That is, if a meaningful correlation exists between soil type and S_{1000}, the best estimate of the relative compressibility index will have little significance during this exploratory hypothesis stage. A refined statistical analysis could later follow.

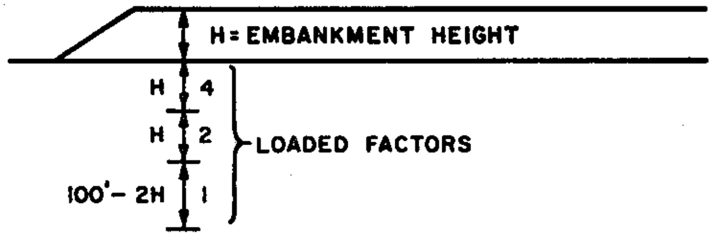
The relative compressibility index is then multiplied by the soil thickness to which a particular soil category has been assigned. The summation of these products are calculated to an arbitrary depth of 100 ft below original ground.

In the event the boring profile does not extend the full 100 feet, a soil category of one is assigned to the uncategorized portion of the soil profile. This index is defined as the soils category index (S.C.I.). A set of typical calculations taken from District 01 are shown on Table 4.

The S.C.I. is then multiplied by the log of the embankment height to adjust for differential embankment thicknesses. A plot is prepared showing SCI x log of embankment height vs S_{1000} (see Fig. 5A). The data on Fig. 5A represent 90 plots from four districts. In order not to confound the analysis at this stage, no locations employing surcharge data were plotted. As can readily be seen, the randomness of the data does not permit the calculation of a useful correlation between these two variables. The hypothesis that a high positive correlation would be found is unsubstantiated by the data.

The next step was to presume that the location of the different soil layers beneath the embankment would influence actual amounts of settlement measured. The contention was that a reduced stress distribution occurred with depth.

To account for this variable a set of loaded factors were applied to the formerly calculated products of SCI x embankment thickness. The procedure was to assign a relative weight of 4 to the soil layers down to a depth equal to the height of embankment. A loaded factor of 2 was assigned from this level down through another equal increment. A factor of 1 was assigned to the remaining distance down to 100 ft. below original ground. A graphic summary of this scheme is shown below. Typical calculations are shown on Table 4.



A plot of loaded factors vs S_{1000} is shown on Figure 5B. Again, the two variables can be seen to have a very low correlation; certainly too low a correlation to be of any predictive value in this work. The unfruitful results of these soil correlational studies force us to conclude that this overall problem is unsolvable by the approaches attempted.

4. ANALYSIS OF ACTUAL AND CONTRACT WAITING PERIODS

Figure 6 is a plot of actual waiting periods vs. contract waiting periods for 112 cases where actual dates of surcharge removal were recorded by field personnel.

With reference to the solid 45 degree line, 35% of the structures had longer actual waiting periods than the corresponding contract waiting periods for that structure while 62% showed shorter actual waiting periods than corresponding contract waiting periods.

Because a few days one way or the other would alter the above percentages considerably, it was thought advisable to contrast only the more extreme cases. To this end an upper and lower criterion group were established. Data above the upper dash line define those cases where the actual waiting period exceeded the contract waiting period by more than 50% for a particular structure. Similarly, data below the lower dash line depict those cases where the actual waiting period was less than 50% of the contract waiting period. Nineteen cases fell above the upper criterion line and 15 cases fell below the lower criterion line. Thus, 30% of all actual waiting periods (surcharge condition only) were either more than 50% or less than 50% of the corresponding contract waiting period for that structure. The next logical question is: Do these two criterion groups differ in any significant way? Table 5 shows a tabulation of the various indeces with respect to these two groups. NO significant trend is observable between upper and lower criterion groups.

5. SURCHARGE ANALYSIS

A tabulation of surcharge data (116 plots) vs. nonsurcharge data (301 plots) for each of the indices investigated is shown on Table 6. The distributions are based on the number and percent of cases falling within each of the ranges assigned to each optical coincidence card (with the exception of Figure 8A). Total numbers and percentages are also shown on Table 6. For example, with regard to Factor A, 55 of the 116 surcharge plots or 47% of the surcharge data fell within the 0-10% range for Factor A. These calculated percentages for surcharge vs. nonsurcharge data are plotted on Figures 7 and 8. The following conclusions are based upon an examination of these plots.

a. Figure 7A. Percent Residual Settlement (Factor A)

At the highest values of percent residual settlement (>30%), nonsurcharge data occurs with an incidence of slightly greater than 2½ times that of surcharge data. This finding is in agreement with theory and practice that surcharges tend to accelerate the rate of settlement.

b. Figure 7B. Settlement/Embankment Ratio (Factor B)

The highest ratio, > .060, consequently most critical to the post construction settlement problem, are found to occur almost seven times as frequently among surcharge data than nonsurcharge data. Since Figure 8D shows that the distribution of embankment heights with respect to surcharge and nonsurcharge plots are very similar, we can conclude that the designers have judiciously placed surcharges where settlement is a problem (Figure 7B) and the use of the surcharges is essentially beneficial (Figure 7A).

c. Figure 7C. Residual Settlement/Embankment (Factor C)

The ratio of residual settlement to embankment height (Factor C) is a dubious measure of the degree of the bump problem.

d. Figure 8A and 8B. Thirty-day Settlement and 1,000-Day Settlement.

The importance of surcharge in accelerating the rate of settlement can perhaps best be indirectly evaluated by comparing the ratio of surcharge to nonsurcharge settlement data for the extreme condition (settlement 1.00 foot) corresponding to each of the two time periods, S_{30} and S_{1000}. These ratios are 4.7 to 1 and 2.5 to 1, respectively. That is, at 30 days after the completion of embankment construction (for nonsurcharge cases), or surcharge construction (for surcharge cases), there were 4.7 times as many surcharge plots as nonsurcharge plots with recorded settlements in excess of 1.00 foot. At 1,000 days after the unit was installed the ratio of surcharge plots compared to nonsurcharge plots with recorded settlements greater than 1.00 foot was reduced to 2.5 to 1. The relative benefits of surcharge upon accelerating the rate of settlement is thus seen to be almost twice as great after 30 days than after 1,000 days assuming all other variables are held constant (e.g., the fact that surcharge would more likely be designed for use where greater settlement is anticipated). This ratio of relative benefits demonstrates that surcharges can be beneficial over relatively short times.

e. Figure 8C. Contract Waiting Period - Days.

Only those contract waiting period (Figure 8C) in excess of 90 days indicate a trend toward longer contract waiting periods being associated with surcharge construction. Contract waiting periods greater than 90 days occur 2½ times as frequently when surcharges are used than when they are not used. However, the magnitude of the surcharge does not appear to be systematically related to the contract waiting period.

f. Figure 8D. Embankment Height - Ft.

The similarity of the distribution of embankment heights under surcharge and no-surcharge conditions tends to add credence to the foregoing conclusions. If the actual surcharge thicknesses are added to the surcharge bars on Figure 8D (which represents the embankment heights only, for both surcharge and nonsurcharge conditions) then a small amount of surcharge data would be pushed to the right of each embankment interval resulting in the bar heights appearing more uniform than they presently appear.

6. MAINTENANCE AND MATERIALS AND RESEARCH CORRELATION STUDY

a. Background Information

In November of 1966, the Maintenance Department reported 1566 structures throughout the State where settlement at structure approaches constitute a maintenance problem (see Table 7). Of these we have settlement log time plots for 212 settlement units out of the total Materials and Research sample of 911. Of the 116 cases of surcharge under study 28 cases were reported by Maintenance.

The total highway system includes approximately 10,000 structures. Assuming all structures were surveyed, the Maintenance Department has reported bump problems at approximately 16% of the structures on our highway system.

b. Surcharge Data

Figure 9: Presumption: $(S_{1000} - S_{EW})$ is an index measurement of bump severity.

(1) Of 116 surcharge cases contained in our file, the Maintenance Department reports a bump problem on 28 of the 111 approaches or 25% of the cases investigated. Those five approaches completed after the Maintenance survey (Nov. 1966) are shown as solid triangles on Figure 9.

(2) Of the 28 cases reported by Maintenance 17/28 or 61% have $S_{1000} - S_{EW}$ of less than 0.10 ft. This order of magnitude is sufficiently small to question whether or not a minimum of 0.20 ft. for S_{1000} is a low enough criterion for those settlement plots which warrant investigation in terms of the bump problem at bridge approaches.

(3) Cases reported by Maintenance do not correlate significantly with increasing $(S_{1000} - S_{EW})$ as had been hypothesized. Above $(S_{1000} - S_{EW})$ of 0.10 ft., 11/29 or 38% of the cases were reported by Maintenance. Below a differential of 0.10 ft., 28% of the cases were reported by Maintenance. While the trend is in the proper direction, the results are not statistically significant.

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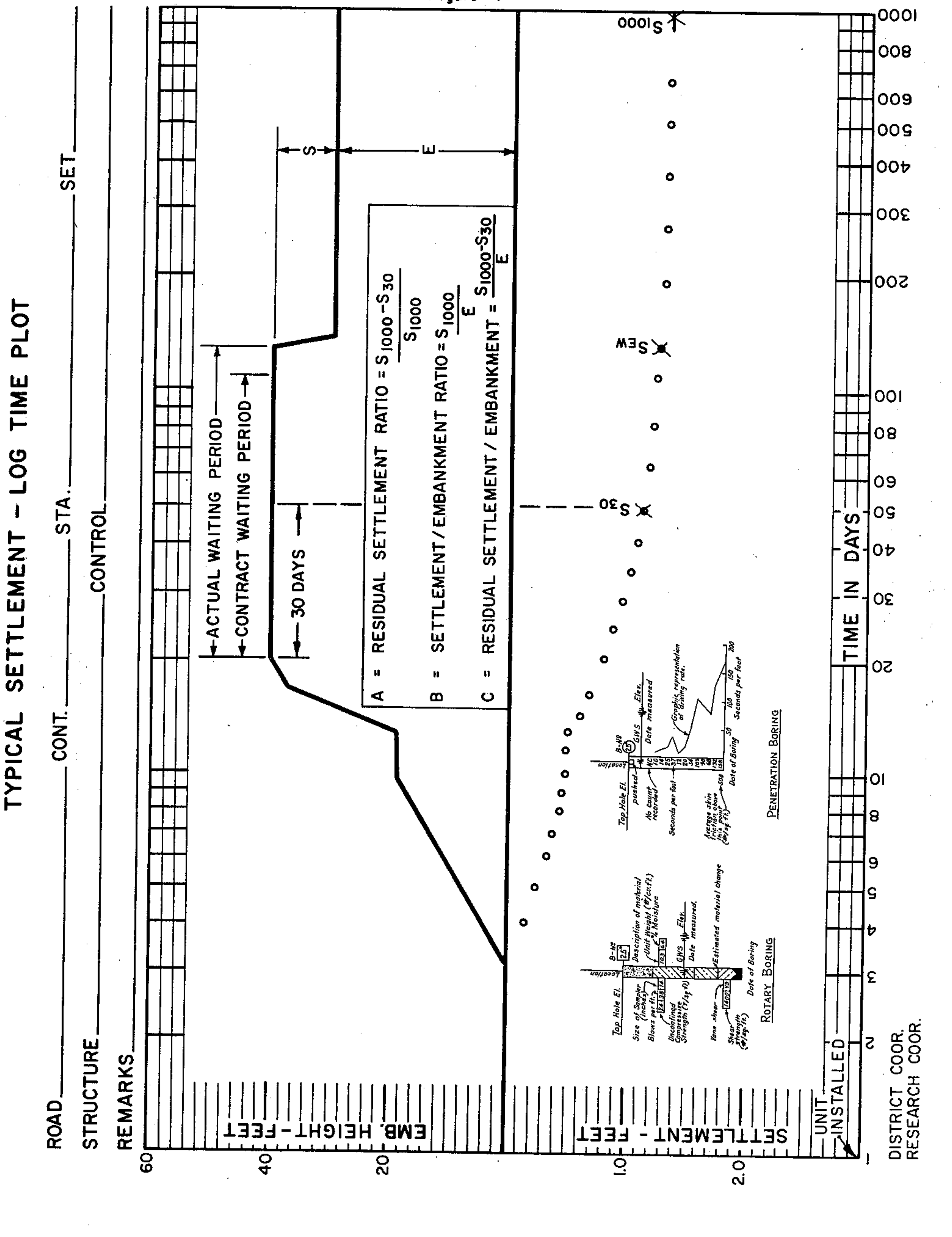
Figure 1



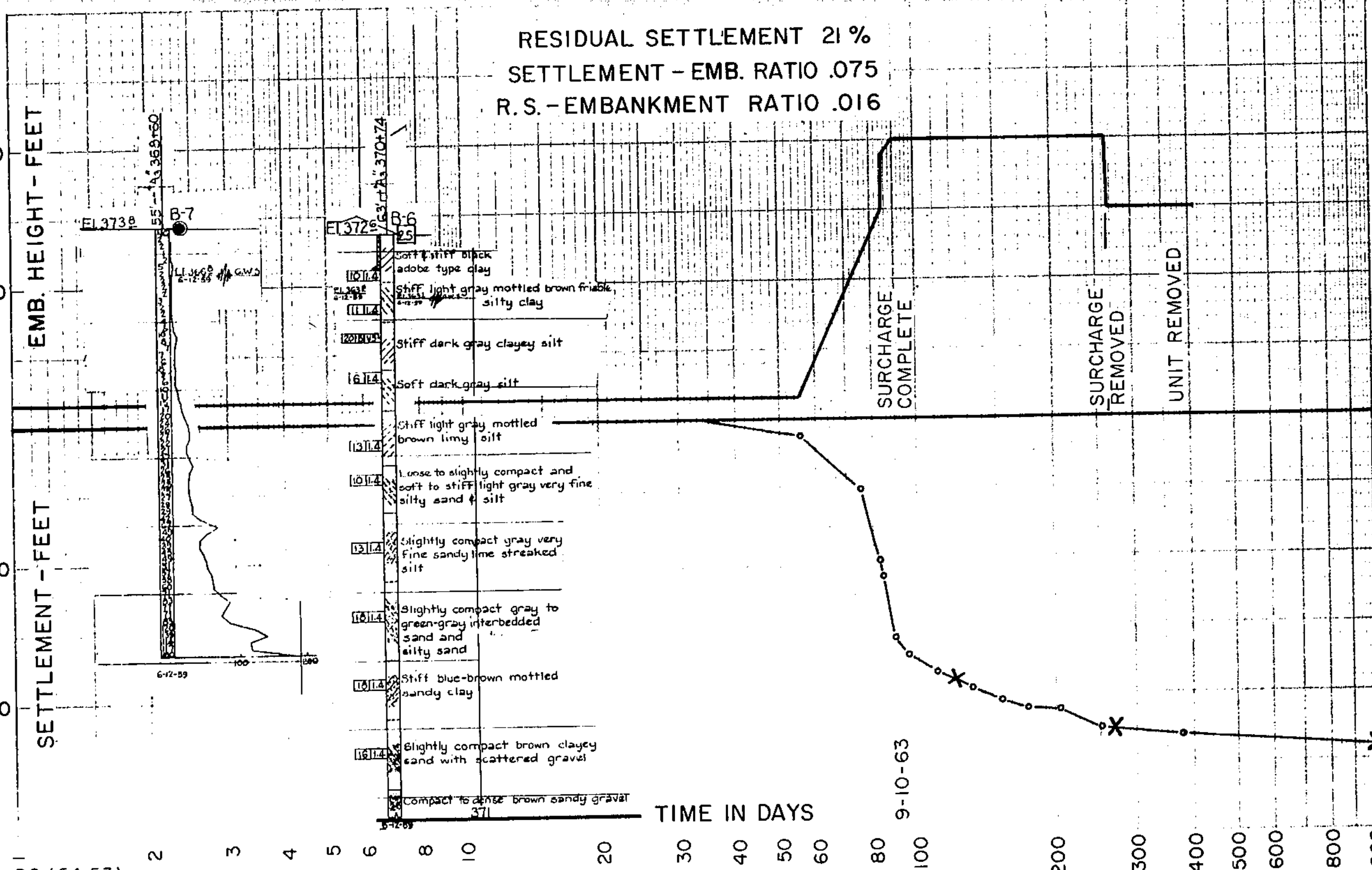
TYPICAL SETTLEMENT - LOG TIME PLOT
ROAD
CONT.
STA.
SET
STRUCTURE
CONTROL
REMARKS
EMB. HEIGHT - FEET
SETTLEMENT - FEET
60
40
20
1.0
2.0
ACTUAL WAITING PERIOD
CONTRACT WAITING PERIOD
30 DAYS
S
E
A = RESIDUAL SETTLEMENT RATIO = $\frac{S_{1000}-S_{30}}{S_{1000}}$
B = SETTLEMENT / EMBANKMENT RATIO = $\frac{S_{1000}}{E}$
C = RESIDUAL SETTLEMENT / EMBANKMENT = $\frac{S_{1000}-S_{30}}{E}$
S_{1000}
S_{EW}
S_{30}
ROTARY BORING
PENETRATION BORING
UNIT INSTALLED
TIME IN DAYS
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
200
300
400
500
600
800
1000
DISTRICT COOR.
RESEARCH COOR.

MATERIALS & RESEARCH DEPARTMENT SETTLEMENT DEVICE INSTALLATION

ROAD 4-CC-680 PM 7.02 CONT. 63-4T13C13-I STA. 368+45 Rt. 30' SET 6-11-63

STRUCTURE Danville OH, South Approach CONTROL 180 day W.P. Surcharge 10'

REMARKS BR # 28-196



DC (54,53)
RC (23,16)

Figure 2

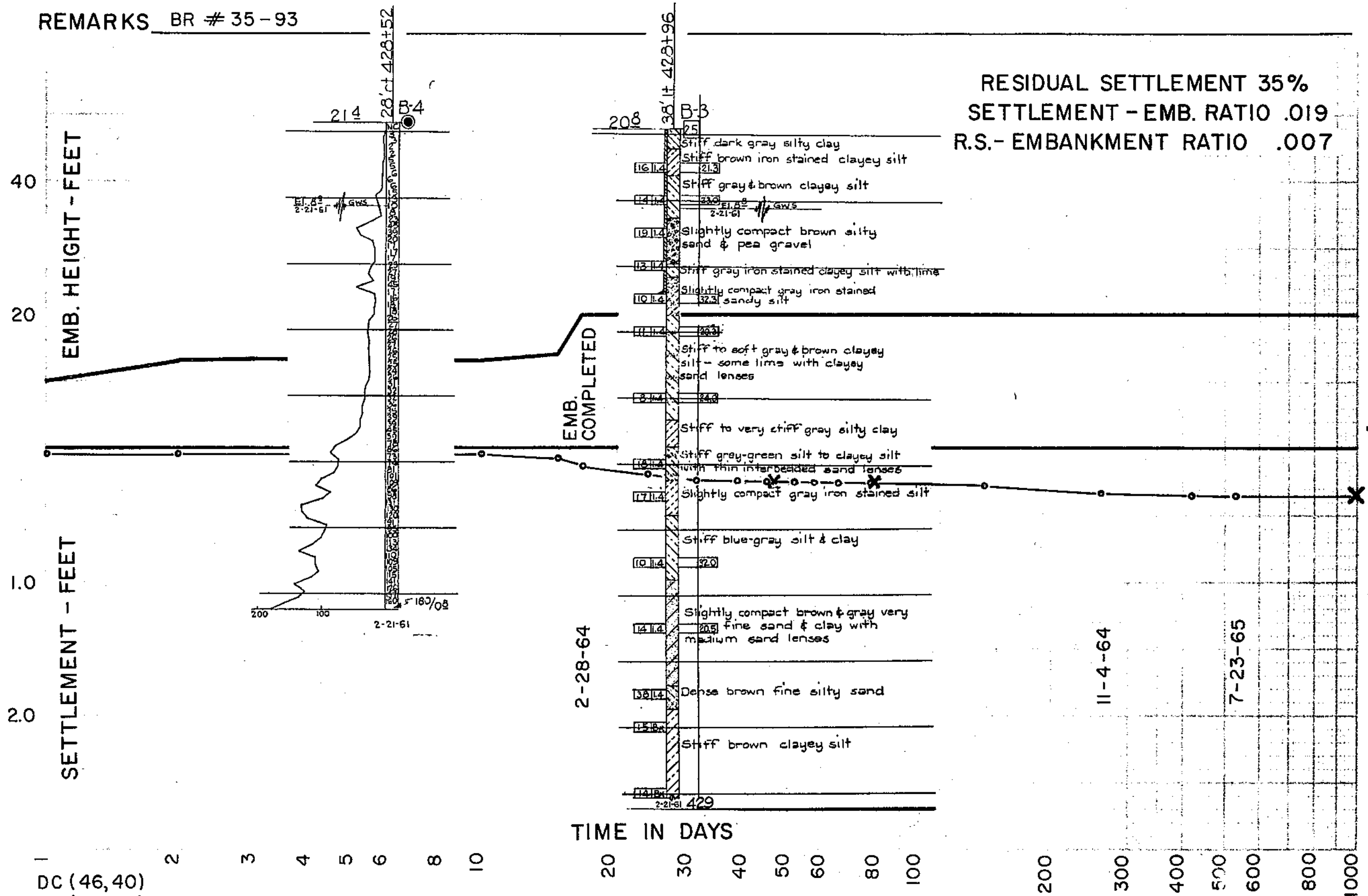
Figure 3

MATERIALS & RESEARCH DEPARTMENT SETTLEMENT DEVICE INSTALLATION

ROAD 4 - SM - 114 PM 3.15 CONT. 64-4T13C30-IP STA. 429 + 18 at ℄ SET 2-11-64

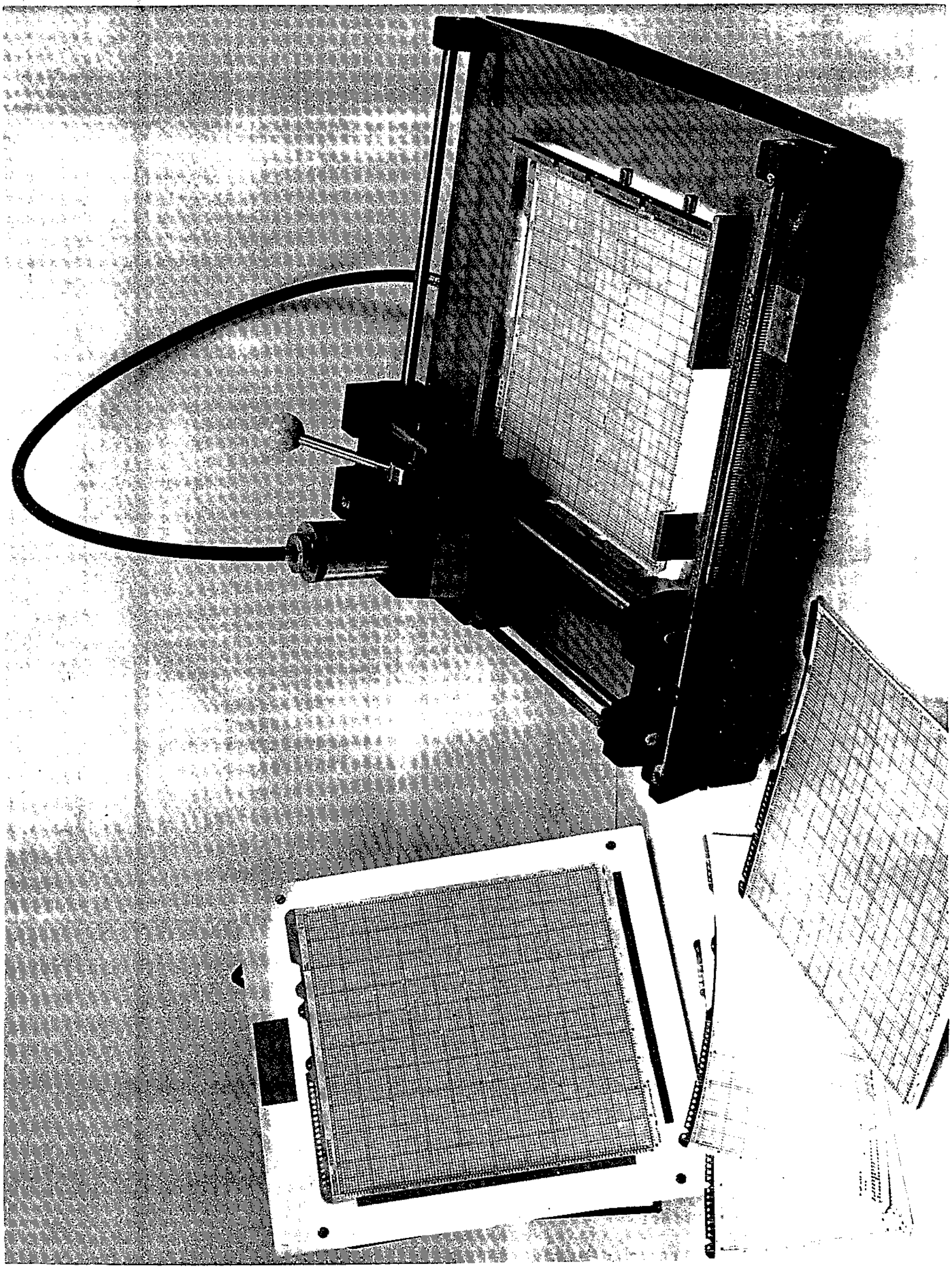
STRUCTURE 5 Points Separation, North Approach CONTROL 60 day W.P.

REMARKS BR # 35 - 93



DC (46, 40)
RC (36, 116)

Figure 4



EQUIPMENT USED IN OPTICAL COINCIDENCE STUDY

CORRELATIONAL PLOT OF S_{1000} WITH PRODUCT OF SOIL CATEGORY INDEX TIMES LOG OF EMBANKMENT HEIGHT (UNLOADED AND LOADED FACTORS COMPARED)

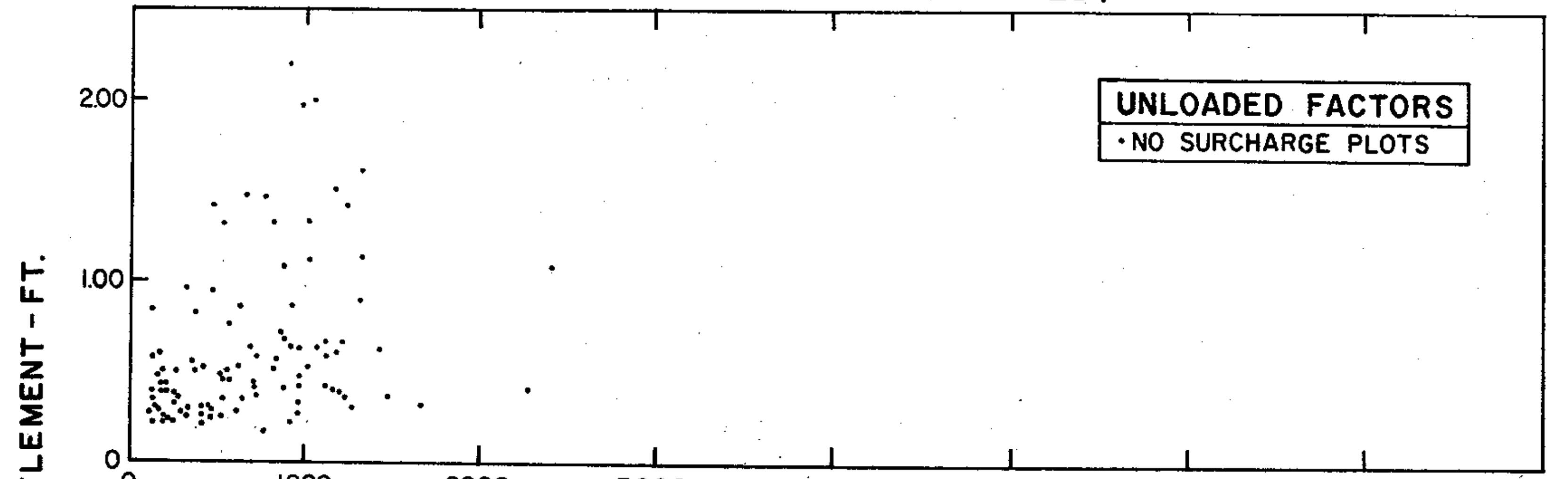


Fig. 5A UNLOADED SCI X LOG OF EMBANKMENT HEIGHT

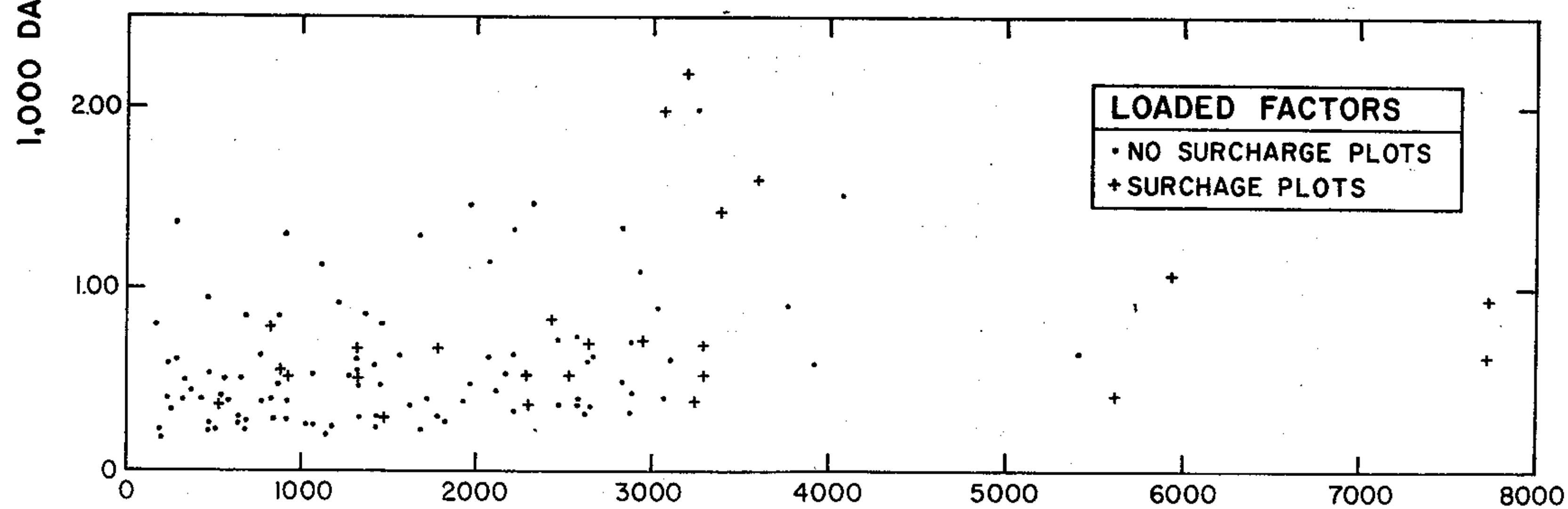


Fig. 5B LOADED SCI X LOG EMBANKMENT HEIGHT

Figure 6

PLOT OF ACTUAL WAITING PERIOD VS CONTRACT WAITING PERIOD FOR SURCHARGE DATA

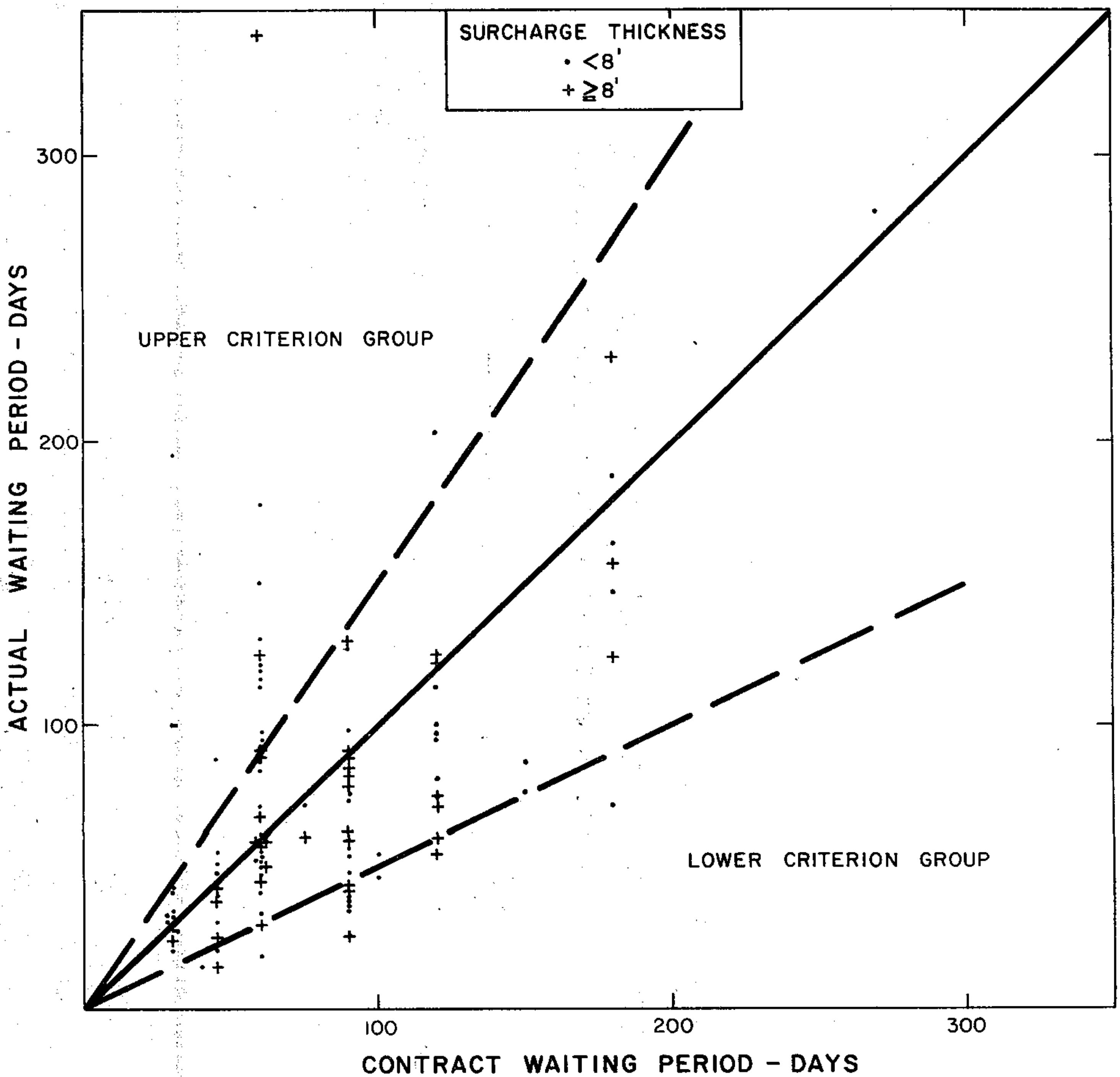


Figure 7

ANALYSIS OF COMPARISON OF DIFFERENCES IN PERCENT OF CASES BETWEEN SURCHARGE AND NO-SURCHARGE DATA FOR DIFFERENT RANGES OF INDICES

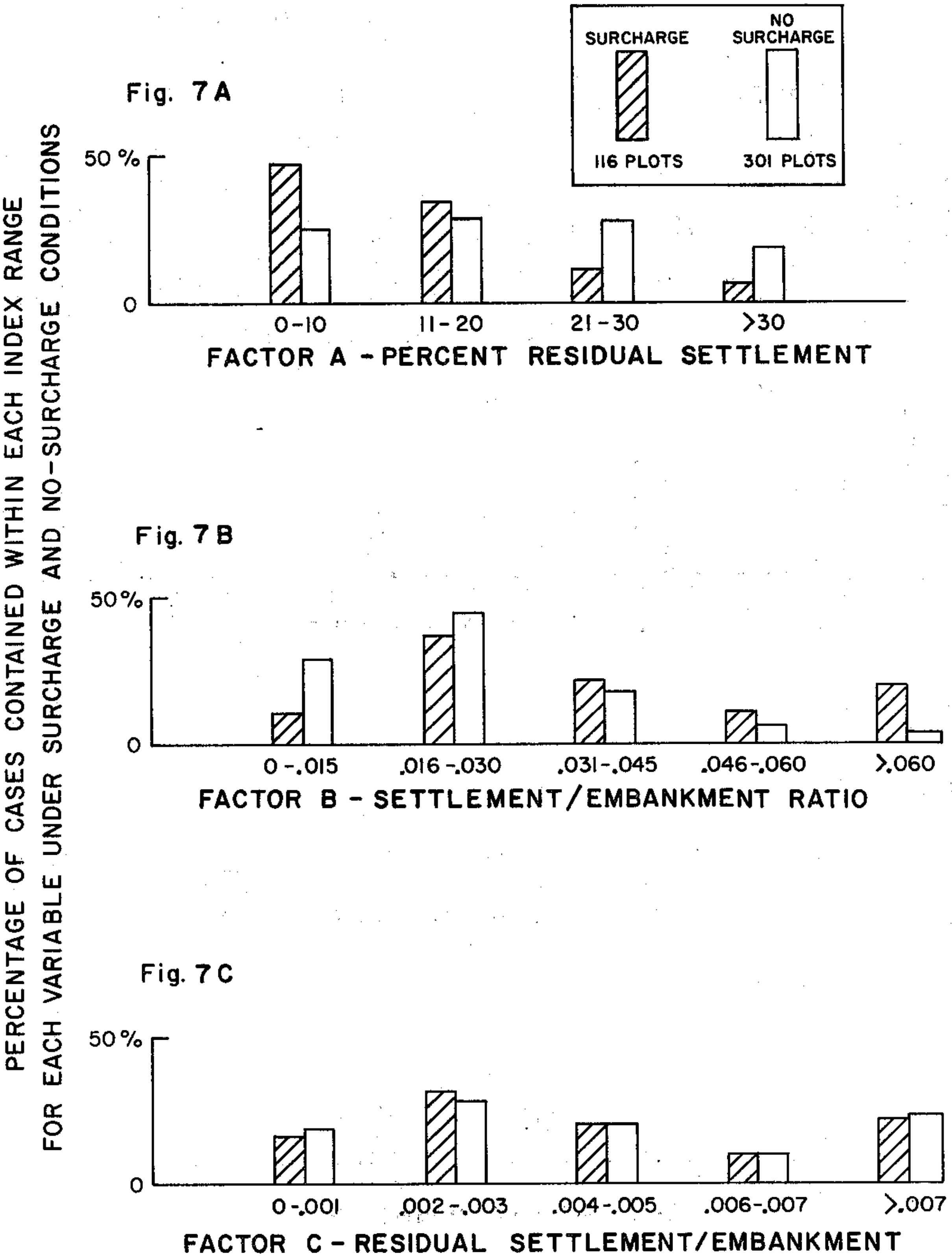


Figure 8

ANALYSIS OF COMPARISON OF DIFFERENCES IN PERCENT OF CASES BETWEEN SURCHARGE AND NO-SURCHARGE DATA FOR DIFFERENT RANGES OF INDICES

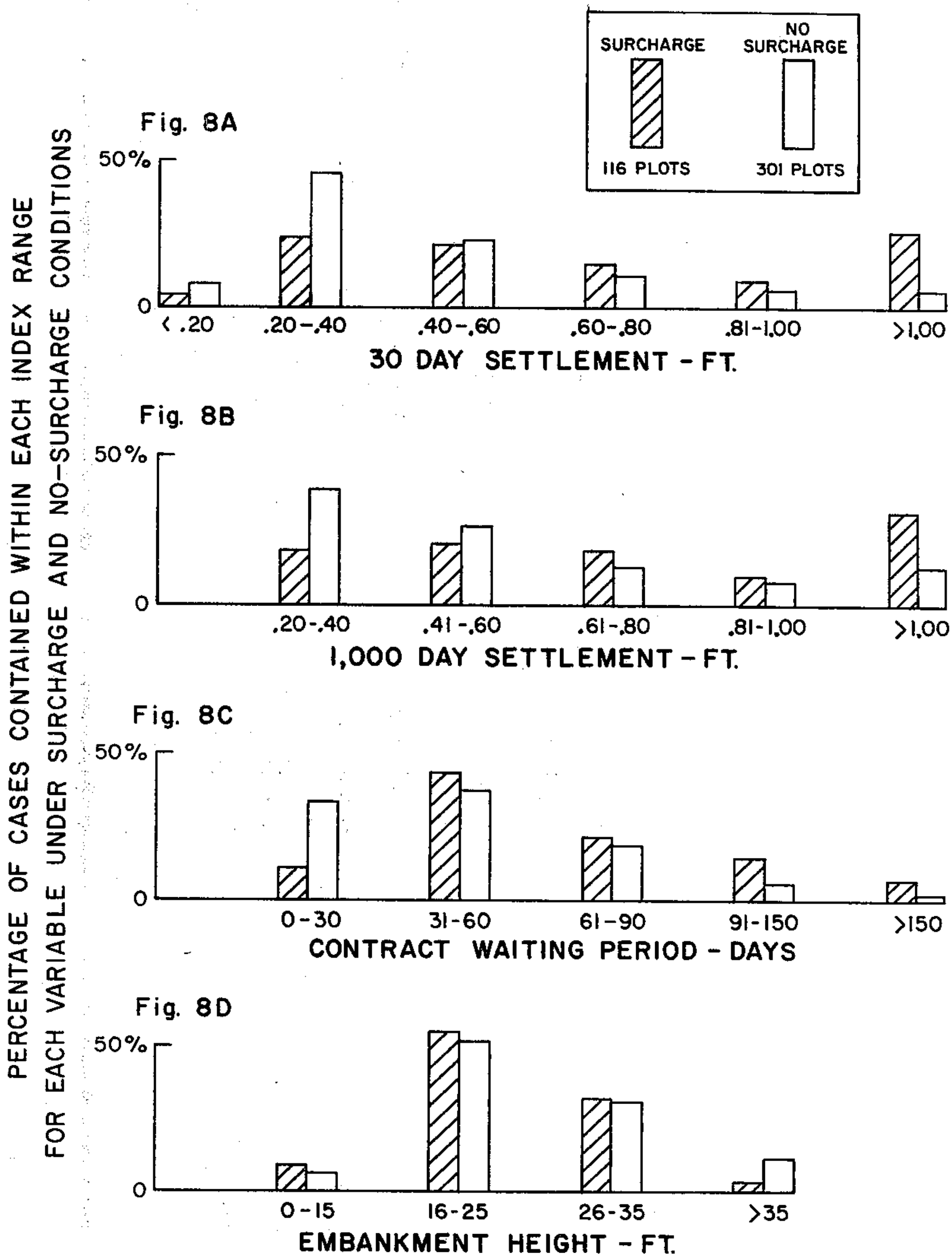


Figure 9

CORRELATIONAL STUDY BETWEEN ESTIMATE OF BUMP SEVERITY ($S_{1000} - S_{EW}$) AND S_{1000}

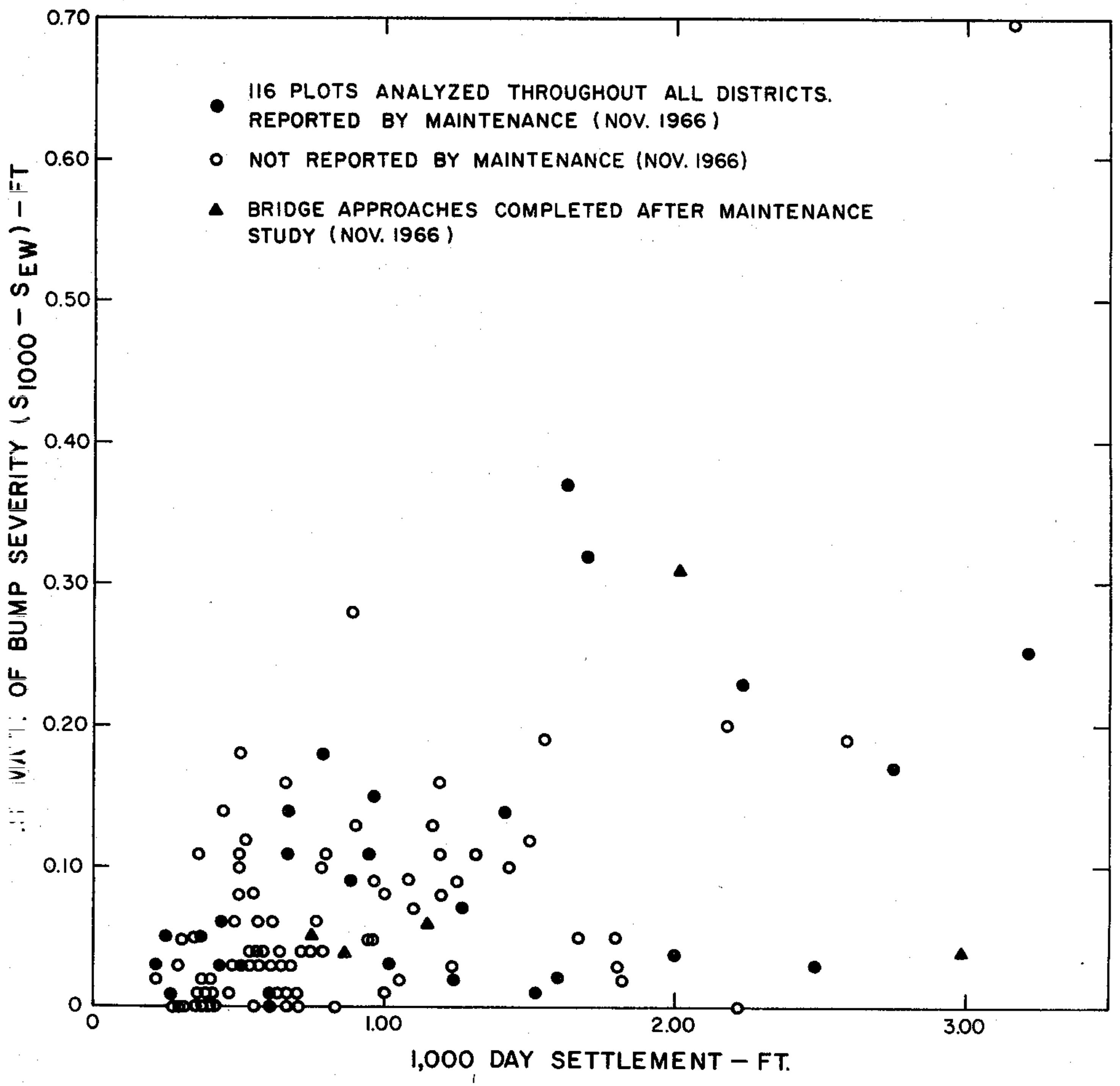


TABLE 1

Identification of Variables Analyzed by Use of Optical Coincidence

Variable Identification	Formula or Units	Interval Range or Description	Card No.	Card Color
E (Embankment Height)	Feet	0-15 16-25 26-35 >35	0 1 2 3	Brown
S (Surcharge Thickness)	Feet	1-3 4-7 >7 Surcharge Card (cards 0,1,2 combined)	0 1 2 6	Gray
	Yes-No	Settlement Reading After Surcharge removed	4	White
WP_c (Contract Waiting Period)	Days	0-30 31-60 61-90 91-150 >150 None Specified	0 1 2 3 4	Red
S_{30} (30-day Settlement)	Feet	0-0.15 0.16-0.30 0.31-0.50 0.51-1.00 >1.00	0 1 2 3 4	Orange
S_{1000} (1000-day Settlement)	Feet	0.20-0.40 0.41-0.60 0.61-0.80 0.81-1.00 >1.00	0 1 2 3 4	Green
Factor A (Residual Settlement Ratio)	$\frac{S_{1000}-S_{30}}{S_{1000}}$	0-10 11-20 21-30 >30	0 1 2 3	Yellow
Factor B $\left(\frac{\text{Settlement}}{\text{Embankment}}\right)$	$\frac{S_{1000}}{E}$	0-.015 .016-.030 .031-.045 .046-.060 >.060	0 1 2 3 4	Purple
Factor C $\left(\frac{\text{Residual Settlement}}{\text{Embankment}}\right)$	$\frac{S_{1000}-S_{30}}{E}$	0-.001 .002-.003 .004-.005 .006-.007 >.007	0 1 2 3 4	Blue
Maintenance Department Report (1966)	Yes-No	—	0	White

TABLE 2

Distribution of Sources From Which Settlement Plots at Structure Approaches are Entered Into Retrieval System

District	Number of Contracts	Number of Structures	Number of Plots Entered Into Retrieval System	Number of Plots Acceptable For Analysis
01	10	13	28	8
02	7	8	14	7
03	13	22	40	18
04	45	82	179	86
05	24	35	85	35
06	17	33	55	36
07	104	230	362	169
08	8	17	32	14
09	0	0	0	0
10	13	21	59	16
11	14	31	57	28
	255	492	911	417

A minimum of 0.20 feet of recorded settlement is set as the lower limit for the preparation of a settlement log-time plot.

TABLE 3

TYPICAL EXAMPLES OF SOIL TYPES ARRANGED IN ORDER OF RELATIVE SETTLEMENT

HIGHEST ⟵⟶ LOWEST

7	6	5	4	3	2	1
Soft clay	Soft damp silty clay	Loose or soft silt	Fine to medium sandy silt	Compact to dense sandy clayey silt	Stiff or very stiff silty clay	Loose silty gravelly sand
Peat & wood with clay	Very soft organic silt	Very soft fine sandy clayey silt	Slightly compact micaceous silty fine sand	Firm silty to sandy clay	Stiff silt	Dense or compact silty sand
Soft organic silty clay	Loose or soft clayey silt	Soft clayey micaceous silt	Loose to compact fine to medium sand & interbedded silty clay layers	Soft sandy gravelly clay	Stiff silt very fine to fine & medium to very coarse sand layer with clay	Very loose fine sand
Wet clay	Soft silty clay with some lime, organic matter and occasional sand lenses	Soft to stiff clay	Loose very fine to fine slightly silty sand with fine mica	Slightly compact layers of silty sand and silt	Very stiff fine sandy clay	Slightly compact silty very fine sand
Very soft adobe & silty clay	Very loose or soft silt	Slightly compact silt, some clay	Loose fine sandy silt	Dense sandy silt	Stiff clay with some sand	Very loose to loose fine sand some silt binder
Black adobe clay (penetrometer <5)	Soft limy silty clay	Sandy clay	Slightly compact silt	Loose very fine sand - some clay	Very dense silt	Sand & silt lenses
Very soft silty clay	Soft silt & clay	Very loose organic clayey silt & fine sand	Loose silt with thin gravel	Compact to dense limy silt	Hard gravelly silty clay	Dense gravel with clay binder
Very soft clayey silt with abundant peaty material	Very soft organic sandy clay	Soft organic silty gravelly clay	Slightly compact clayey very fine sand	Dense slightly clayey fine sand with organic material	Slightly compact sand-some silt	Roadbed embankment
Soft silty clay to clay	Damp clay					
Organic clay						

TABLE 4

Examples of Steps Used in the Calculation of the Soil Category Index Under Loaded and Unloaded Conditions

Soil Category	7	6	5	4	3	2	1
Relative Compressibility Index (RCI)	50	30	20	6	4	2	1

Plot No.	SOIL LAYER						Remaining Depth to 100'	UNLOADED CALCULATIONS				S_{1000}
	#1	#2	#3	#4	#5	#6		Unloaded SCI	Emb. Ht.	Log_{10} Emb. Ht.	Log Emb. Ht. X SCI	
	(Soil Category—Layer Thickness)											
1	5-10	4-6	1-27	2-22	1-4		31	372	24	1.38	513	1.29
5	1-45						55	100	25	1.40	140	.58
8	1-28	4-16	1-11	2-4	3-46	1-9	-14	494	45	1.65	815	.56
10	1-40						60	100	21	1.32	132	.85
17	6-15	5-8					77	687	26	1.41	969	1.97

Example of calculation of unloaded SCI

(Calculations are based on plot No. 1. All the above data were obtained from Dist. 01)

(20x10)+(11x6)+(1x27)+(2x22)+(1x4)+31 = 372 ← Unloaded SCI

RCI for soil Category 5

Thickness of 1st soil layer below original ground

Remaining depth to 100'

Plot No.	LOADED CALCULATIONS					S_{1000} (Repeat)
	O.G. to H_1 4Σ (RCI x Thickness)	H_1 to H_2 2Σ (RCI x Thickness)	H_2 to 60' Σ (RCI x Thickness)	Loaded SCI	Log Emb. Ht. X Loaded SCI	
1	4 [(20x10)+(11x6)+(1x8)] = 1096	2 [(1x19)+(2x5)] = 58	(2x12) = 24	1158	1598	1.29
5	4 (1x25) = 100	2 [(1x20)+(1x5)] = 50	(1x10) = 10	160	224	.58
8	4 [(1x28)+(11x16)+(1x1)] = 820	2 [(1x10)x(2x4)+(6x1)] = 48	- = 0	868	1432	.56
10	4 (1x21) = 84	2 [(1x19)+(1x2)] = 42	(1x18) = 18	144	190	.85
17	4 [(30x15)+(20x8)+(1x3)] = 2552	2 (1x26) = 52	(1x9) = 8	2312	3260	1.97

TABLE 5

Tabulation of Various Indices Based Upon Upper and Lower Criterion Groups

	Dist.	Research Coordinates	Waiting Period		Factor			Settlement		Emb.	Surcharge
			Contract	Actual	A	B	C	S_{1000}	S_{30}		
Upper Criterion Group	03	33,10	120	204	13%	.023	.003	.75	.65	33	5
	05	02,25	60	150	7%	.029	.002	.61	.57	21	5
		31,25	60	113	24%	.025	.006	.70	.53	28	6
		49,25	60	178	18%	.075	.013	.60	.49	8	2
		60,25	60	116	0%	.040	0	.28	.28	7	5
		61,25	60	119	0%	.043	0	.30	.30	7	5
		65,25	60	94	13%	.020	.003	.39	.34	19	5
		66,25	60	97	8%	.015	.001	.39	.36	26	4
	07	33,40	60	125	10%	.070	.007	1.27	1.14	18	15
		35,40	60	122	6%	.059	.004	1.24	1.16	21	9
		61,40	60	342	10%	.068	.007	2.48	2.22	36	12
		25,41	30	100	43%	.040	.017	.88	.50	22	4
		26,41	30	100	36%	.026	.009	.50	.32	19	4
		27,41	60	120	15%	.030	.005	.62	.53	21	6
		28,41	60	130	9%	.025	.002	.46	.42	18	6
		55,41	45	88	10%	.017	.002	.48	.43	27	7
		22,43	60	91	18%	.028	.005	.97	.80	35	16
		23,43	60	92	3%	.044	.001	.66	.64	15	13
	08	21,70	30	195	20%	.020	.004	.40	.32	20	4
Lower Criterion Group	01	24,00	365	97	24%	.052	.012	.89	.68	17	5
		26,00	180	72	17%	.015	.003	.35	.29	23	5
	04	06,15	40	16	17%	.016	.003	.30	.25	19	5
		98,15	100	47	8%	.036	.003	1.09	1.00	30	5
		03,16	90	39	6%	.031	.002	.68	.64	22	5
		48,16	90	40	20%	.029	.006	.50	.40	17	5
	05	08,25	120	55	5%	.059	.003	1.23	1.17	21	8
		63,25	90	36	21%	.029	.006	.66	.52	23	5
		64,25	90	40	6%	.012	.001	.51	.48	41	10
	07	03,40	90	27	4%	.032	.001	.57	.55	18	10
		06,40	90	37	4%	.042	.002	1.02	.98	24	11
		07,40	90	44	5%	.009	0	.26	.25	27	8
		99,40	60	20	13%	.050	.007	1.18	1.03	23	5
		57,41	45	21	7%	.032	.002	1.10	1.02	33	6
		97,41	45	16	7%	.013	.001	.56	.52	42	10

CONCLUSIONS

No significant correlations between Upper and Lower Criterion Groups on any of the variables listed. See text, page 9 for definition of Criterion Groups.

TABLE 6

Tabulation of Surcharge vs Non-Surcharge Data

Type of Settlement Plot	Number of Plots	VARIABLE RANGES											
		Embankment Height - Ft.											
		0-15	%	16-25	%	26-35	%	35	%	———		———	
Surcharge	116	11	9	64	55	37	32	4	3				
No Surcharge	301	19	6	155	52	92	31	>35	12				
Total	417	30	7	219	53	129	31	39	9				
		Contract Waiting Period - Days											
		0-30	%	31-60	%	61-90	%	91-150	%	>150	%	None Specified in Specials	%
Surcharge	116	13	11	50	43	25	22	16	14	8	7	4	3
No Surcharge	301	99	33	110	37	53	18	18	6	5	2	16	5
Total	417	112	27	160	38	78	19	34	8	13	3	20	5
		(S_{30}) 30-Day Settlement - Ft.											
		<.20	%	.20-.40	%	.41-.60	%	.61-.80	%	.81-1.00	%	>1.00	%
Surcharge	116	5	4	28	24	25	22	18	15	10	9	30	26
No Surcharge	301	24	8	140	46	69	23	32	11	18	6	18	6
Total	417	29	7	168	40	94	23	50	12	28	7	48	11
		(S_{1000}) 1,000-Day Settlement - Ft.											
		———		.20-.40	%	.41-.60	%	.61-.80	%	.81-1.00	%	>1.00	%
Surcharge	116			21	18	24	21	22	19	12	10	37	32
No Surcharge	301			117	39	80	27	40	13	25	8	39	13
Total	417			138	33	104	25	62	15	37	9	76	18
		(Factor A) Percent Residual Settlement											
		0-10	%	11-20	%	21-30	%	>30	%	———		———	
Surcharge	116	55	47	39	34	14	12	8	7				
No Surcharge	301	76	25	84	28	83	28	58	19				
Total	417	131	31	123	30	97	23	66	16				
		(Factor B) Settlement/Embankment Ratio											
		0-.015	%	.016-.030	%	.031-.045	%	.046-.060	%	>.060	%	———	
Surcharge	116	11	10	43	37	26	22	13	11	23	20		
No Surcharge	301	87	29	134	45	53	18	18	6	9	3		
Total	417	98	24	177	42	79	19	31	7	32	8		
		(Factor C) Residual Settlement/Embankment Height											
		0-.001	%	.002-.003	%	.004-.005	%	.006-.007	%	>.007	%	———	
Surcharge	116	19	16	36	31	23	20	12	10	26	22		
No Surcharge	301	56	19	85	28	60	20	31	10	69	23		
Total	417	75	18	121	29	83	20	43	10	95	23		

Retrieval Card Number

0	1	2	3	4	5

TABLE 7

STRUCTURE APPROACHES REQUIRING CORRECTIVE WORK
AS REPORTED BY
DISTRICT MAINTENANCE DEPARTMENTS IN NOVEMBER 1966

Dist.	Structures Reported	Estimate of Settlement	Estimate of Patching	Remarks
01	168	no	yes	An arbitrary numerical value represents corrective work that is now needed or has been done in the past four-year period
02	42	no	no	
03	117	no	no	
04	258	no	no	Specific structure end(s) exhibiting settlement is noted.
05	133	no	no	
06	15	yes	yes	Estimated to nearest 1/8"
07	264	no	no	
08	133	no	no	
09	5	yes	yes	Estimated to nearest 1/2"
10	127	no	no	
11	304	no	no	
Total	1566			